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14. ABSTRACT
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Correlation of in situ measurements of plasma irregularities with ground-based scintillation observations

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[1] We present here the first comparison of in situ ion density fluctuations measured by the Planar Langmuir Probe on Communication\Navigation Outage Forecasting System (C/NOFS) with coincident ground-based measurements of scintillation from the Scintillation Decision Aid (SCINDA) network and coherent scatter radar located on Christmas Island (3°N, 157°W) over a 15 month period from May 2008 through June 2009. The Planar Langmuir Probe on C/NOFS measures absolute ion densities from 10 to 10^8 cm^{-3} at a rate up to 1024 Hz. The instrument is conceptually similar to ion traps and retarding potential analyzers that have flown on many past satellite and rocket missions. However, the present design includes advances in electronic capability compared with past designs. Initial results from this study show that in situ density fluctuations observed on magnetic flux tubes that pass over Christmas Island can be used as an indicator of ionospheric radio wave scintillation at that site. This is true even when the measurements are made at horizontal ranges of over 1000 km away from the ground site as long as the field line apex altitudes are less than ~600 km.

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1. Introduction

[2] The Planar Langmuir Probe (PLP) instrument is one of three instruments on the Communication/Navigation Outage Forecasting System (C/NOFS) satellite that measures in situ ion number densities. Along with the Trigger Probe that is part of the Vector Electric Field Instrument (VEFI) and the Retarding Potential Analyzer in the Ion Velocity Meter (IVM) [*Heelis et al.*, 2009], PLP provides measurements of ionospheric ion densities along the orbital track of the satellite. PLP is optimized to make faster measurements than the other two instruments and can measure density fluctuations and power spectral densities at frequencies between 32 and 1024 Hz. These measurements are used to identify and locate highly structured regions of the ionosphere that could interfere with transionospheric radio wave transmission.

[3] Since its initialization in May, 2008, PLP has detected large numbers of highly structured ionospheric regions in the equatorial belt. We will present an overview of these measurements and will present the results of an extensive case study of the relationships between the observation of in situ irregularities, UHF scintillation observed by the Scintillation Decision Aid (SCINDA) network at Christmas Island, and measurements of coherent backscatter irregularities above Christmas Island.

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2. Instrumentation

[4] The PLP is designed to measure absolute ion densities, ion density fluctuations and power spectral densities, electron temperature, vehicle potential, and the energy distributions of ions in the *F* region of the equatorial ionosphere. Ion density and ion fluctuation measurements are the prime goals of PLP and will be the focus of this paper. The PLP sensors are conceptually similar to swept bias Langmuir probes and retarding potential analyzers that have flown on many past satellite and rocket missions [*Hanson and Heelis*, 1975]. However, the present design includes advances in electronic capability compared with past designs. These include: significant improvements in the range, linearity, and high-frequency time response of the logarithmic amplifiers; microprocessor control of software antialias filters; hardware filters that increase the effective sampling range of the A/D converters by flattening the typical power spectral density curve prior to sampling; hardware antialias filters; and, suppression of photoelectron effects and amplifier drift by injection of a variable calibration current into the ion trap logarithmic amplifier.

[5] The PLP instrument contains two independent sensors. The Surface Probe is an electrically isolated flat plate with controllable bias that is directly exposed to the space environment. It is normally held at a potential negative with respect to spacecraft ground and measures saturation ion current. The potential on the Surface Probe can be swept from −5 to +2 V to obtain electron and ion current I-V curves from which the electron temperature can be extracted. The Ion Trap is a grounded electrode mounted beneath a stack of three 80% transmission etched gold grids.

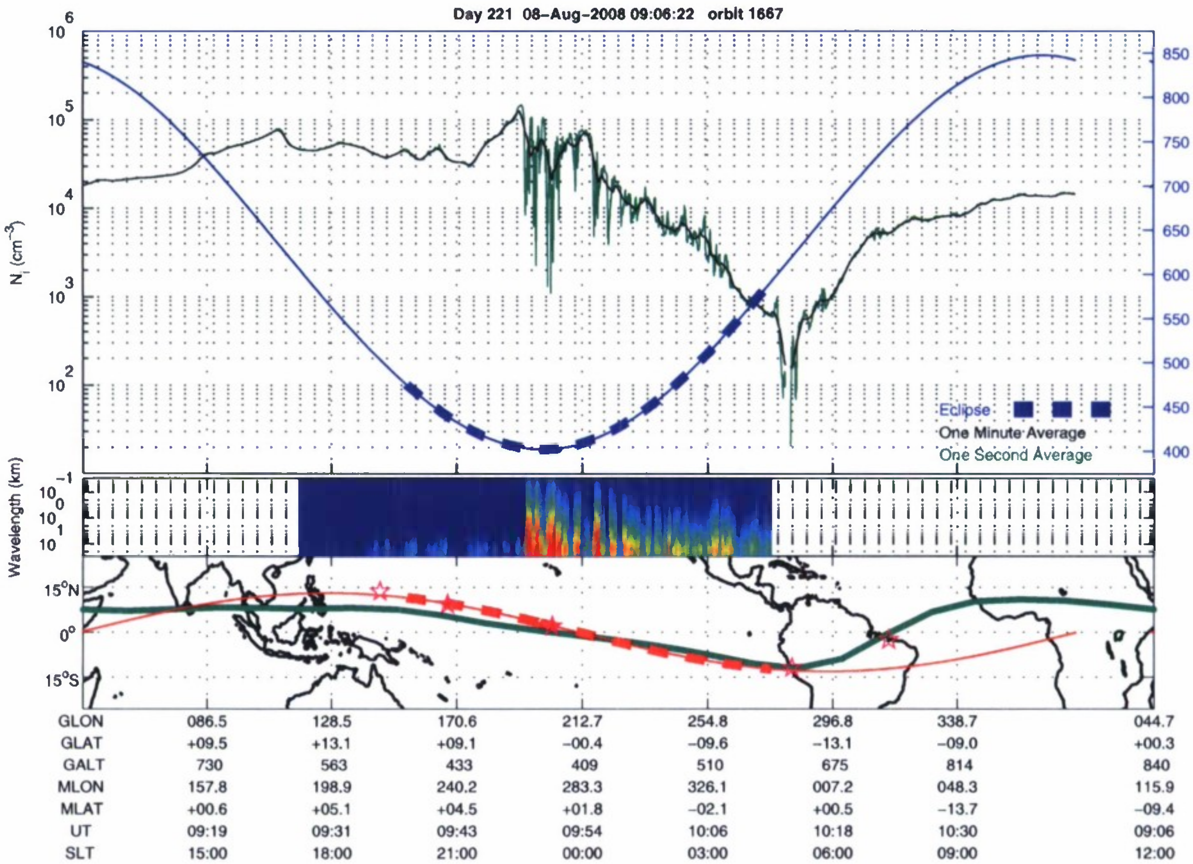

Figure 1. Orbit 1687, 8 June 2008. (top) One min-integrated ionospheric density (black line); one-second integrated density (green line); satellite altitude (blue line). (middle) FFT from the 512 Hz PLP data. (bottom) Map with satellite trajectory and magnetic equator, red and green, respectively. Thick dotted lines indicate when C/NOFS satellite is in darkness.

The outermost grid is held at or near spacecraft ground. The second grid is normally at −5V to allow passage of all ions, but can be swept from −5 to +12V to perform retarding potential analyses. The third grid is an electron repeller and photoelectron suppressor held at −12V. The Ion Trap current is initially sampled at 2 kHz, passed through the appropriate antialias filters and then averaged down to the desired telemetry rate. Available sample rates are 32, 256, 512, and 1024 Hz. PLP is nominally operated at 32 Hz during the day and at 512 Hz during eclipse to reduce telemetry volume. Because it operates at a higher sample rate and has a more reliable density calibration, all of the data presented in this paper were collected with the Ion Trap sensor. The Surface Probe sensor measurements corroborate the Ion Trap measurements, but are not utilized in this study.

[6] The Air Force Research Laboratory (AFRL) maintains a SCINDA [*Groves et al.*, 1997] observation station at Christmas Island (Kiritimati) in the Republic of Kiribati (3°N, 157°W). UHF radio receivers at the site monitor signal amplitude and phase from geostationary radio beacons. Fluctuations in signal amplitude are used to derive the S4 index, a measure of the severity of ionospheric disruption of radio wave transmission. The Christmas Island SCINDA site maintains UHF (~250 MHz) links to two geostationary communications satellites with 300 km altitude ionospheric pierce points at 1.9N, 201.6E and 1.9N, 207.0E, respectively. AFRL also maintains a coherent scatter radar at Christmas Island that is colocated with the SCINDA receivers. The 50 MHz radar measures backscatter from 3 m scale size irregularities in two directions: geographic east and geographic north at zenith angles of 30° and 5.5°, respectively. The beams are oriented such that they are near perpendicular to B at ionospheric heights. Data from the east beam of the radar and both UHF links are used in this study.

3. Distribution of Irregularity Structures

[7] Figure 1 gives a typical example of a single orbit of PLP data centered on local solar midnight. The top panel in Figure 1 shows the measured one second average ion density (green) and one minute average (black) against the left vertical axis. This panel also shows the altitude of the satellite against the right axis with eclipse indicated by the heavy dotted line. The middle panel shows spectrograms of the full 512 Hz data converted into units of distance with spectral power given in arbitrary units. The bottom panel gives the ground track of the satellite (dotted in eclipse) along with the magnetic equator.

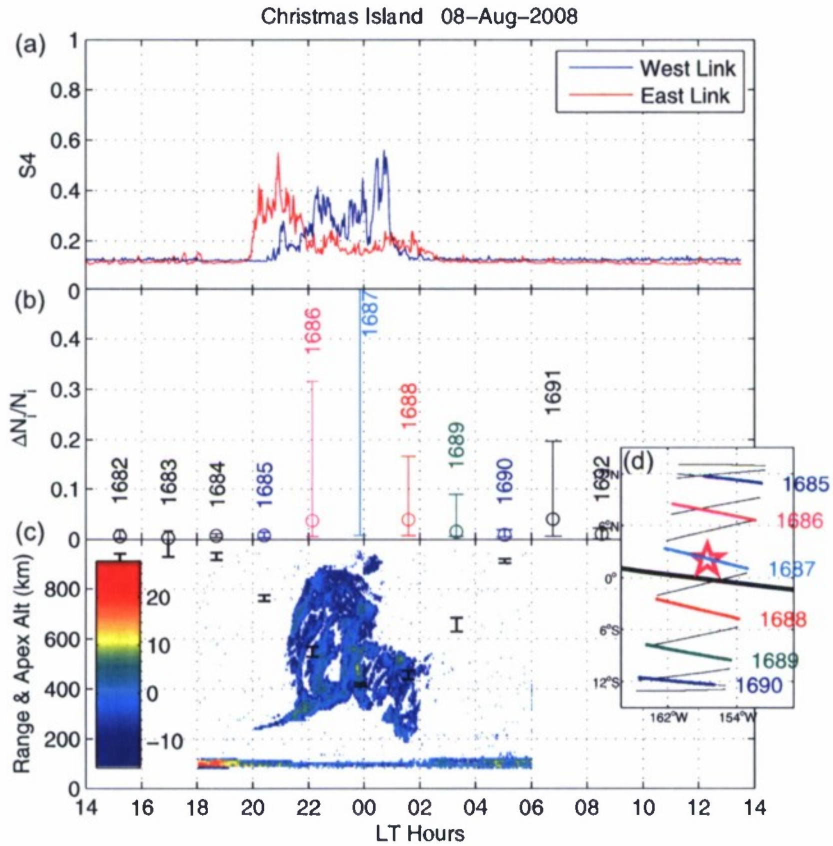

Figure 2. A comparison of SCINDA, PLP, and CSR data from Christmas Island on 8 August 2008. (a) A 244 MHz fixed link SCINDA S4 scintillation index, (b) average $\Delta n_i/n_i$ from PLP during a +/− 5° magnetic longitude window (~10 min) around Christmas Island with the error bars representing the minimum and maximum 1 s $\Delta n_i/n_i$ observed, (c) S/N return from Christmas Island 3 m backscatter radar (in dB) along with the apex altitude range of C/NOFS over the site, and (d) ground tracks of individual C/NOFS passes above Christmas Island (star) with the magnetic equator as a bold black line.

[8] Despite the first year of the C/NOFS satellite mission occurring under historically low–solar activity conditions, PLP has observed significant and frequent structuring of the nighttime ionosphere. The vast majority of these ionospheric structures have occurred post midnight. In the particular example in Figure 1, from 8 August 2008 (orbit 1687), perigee was just premidnight over Christmas Island. From dusk to midnight, the variation in ion density was relatively smooth, but became much more pronounced after midnight with small spatial scale density depletions of 2 orders of magnitude or more. The depletion structures extend over a large longitude range from the central Pacific to South America.

4. Ground-Space Coincidence Study at Christmas Island

[9] One goal of the C/NOFS program is to extend the geographic range of the SCINDA network to regions of the globe that are not currently covered [*de La Beaujardière et al.*, 2004]. SCINDA has more than a dozen ground sites near the magnetic equator equipped with UHF and L band radio receivers to monitor the fidelity of space to ground radio transmissions. They provide reliable nowcasts and short-term forecasts of scintillation conditions in the region near each ground site. However, there are gaps between the sites, particularly over oceans. C/NOFS augments the SCINDA observations with measurements of ionospheric irregularities that cover the entire equatorial region. In order to use these space-based measurements, however, the correlation between the structures and the resulting scintillation must be quantified.

[10] As a first step in this process, we compare in situ density fluctuation measurements made by PLP over the Christmas Island SCINDA site with simultaneous measurements of S4 on the ground. A sample summary data plot from 8 August 2008 is shown in Figure 2. The top panel plots the S4 index measured on the two UHF links as a function of local time. Because of the relatively low solar activity and low TEC values prevalent in the 2008–2009 ionosphere, we only use the SCINDA UHF scintillation measurements as they are more sensitive to ionospheric disturbances than the L band measurements. We have restricted the comparison to times when the C/NOFS satellite was within ± 5° magnetic longitude of Christmas Island. The relevant parts of the ground tracks for each orbit

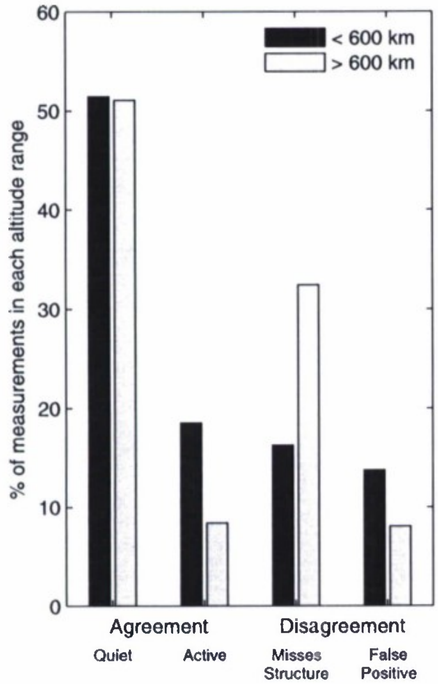

Figure 3. A graphical representation of the data presented in Table 1 showing the percentage of each category of forecast and observation for apex altitudes above and below 600 km.

are shown on the small inset plot. Passes during eclipse are shown in bold color. $\Delta n_i/n_i$ is calculated from the standard deviation of n_i around a 1 s average of n_i. The middle panel shows the mean of the 1 s $\Delta n_i/n_i$ values derived from the PLP measurements plotted against LT during a given pass (with error bars representing the minimum and maximum 1 s values). Orbit numbers are plotted on both the $\Delta n_i/n_i$ plot and the inset. Regions of large $\Delta n_i/n_i$ correspond to the structured ionospheric regions that could disrupt communications. Finally, the bottom panel has two kinds of information. The black error bars plot the range of apex heights of the magnetic field line at the C/NOFS satellite location for each of the data points in the middle panel. Because Christmas Island is close to the magnetic equator, the apex heights are a good approximation of the height of the satellite's flux tube over the ground site. The bottom panel also has a range-time-intensity (RTI) plot from the 50 MHz coherent backscatter radar at Christmas Island. Colors indicate the signal-to-noise ratio of the coherent returns (in dB) from 3 m scale size irregularities along the east beam of the radar.

[11] The data in Figure 2 are an example of excellent agreement between all three diagnostics. The SCINDA receivers measure relatively intense scintillation from 2200–0200 LT (0800–1200 UT) on both links, the radar shows a large plume structure over Christmas Island between 2130–0200 LT (0730–1200 UT), and PLP flies through highly structured ionospheric regions on orbits 1686 through 1689. Orbit 1687 passes almost directly over the ground sites at perigee and shows the most intense in situ structure. Other passes are somewhat removed in latitude from the ground site, but are on field lines that connect with the large coherent structure. These passes also show significant variation in the in situ measurements, indicating that the structures map along the field lines to at least some degree.

[12] We have created these summary plots for all days between May 2008 and July 2009, for which data exist—a total of just over 1500 nighttime orbital passes over Christmas Island. Each orbit is sorted into one of four categories: Agreement-Active, Agreement-Quiet, Disagreement-PLP misses structure, and Disagreement-PLP false positive. For orbits in the Agreement-Active category, the in situ $\Delta n_i/n_i$ measurements agree with the SCINDA measurements that ionospheric structure is present during that orbit or UT. Figure 2 is an example of four sequential orbits that fall into this category. We have assigned a threshold of 5% for $\Delta n_i/n_i$ to be considered significant. We have also imposed a requirement that if $\Delta n_i/n_i > 30\%$ then the corresponding Δn_i must be greater than 10^4 cm^{-3} for the orbit to be considered active. This is done to minimize false positives where the background ionization is simply too small to cause scintillation even if fluctuations are present. For Agreement-Quiet orbits, both the in situ measurements and the SCINDA S4 results agree that no structure is present. In the case of Disagreement-PLP misses structure orbits, the S4 values during the pass are significantly higher than the background, but the in situ ion density show little or no evidence of fluctuation or irregularities. The coherent scatter radar often shows the presence of irregularities in agreement with the S4 results. For Disagreement-PLP false positive, the SCINDA ground measurements indicate no increase in S4, but the PLP in situ measurements show some structure. Most of the time, the radar RTI plot shows no structure in agreement with SCINDA, but there are a few instances where both the PLP and the radar measurements indicate the presence of structure in the ionosphere while there is no impact on the S4 values.

[13] In many of the cases where PLP does not measure irregularity structures but the SCINDA receivers do see scintillation, the apex heights of the field lines at the satellite location are much higher than any structures seen by the radar (see Figure 2, orbit 1685). PLP misses the structure simply because the satellite is in the wrong place. The C/NOFS orbit dictates that the satellite spends a large fraction of its time at high apex heights. Because we do not want to bias the comparison with orbits where PLP does not have a chance to see relevant structures, we have chosen to divide the Christmas Island passes into cases with apex heights either above or below 600 km. This is a somewhat arbitrary division, as a lower-apex height cutoff might give better results. But the majority of radar plumes are seen to reach this altitude and there are enough satellite passes below this altitude for reasonable statistics.

[14] Table 1 gives statistics for the 1525 passes. Approximately 20% of the passes are at apex heights lower than 600 km. Of these, 69% show agreement between the in situ detection of structure and scintillation on the ground or agreement that there is no structure and no scintillation. 16% show disagreement where PLP does not detect structure when ground-based scintillation is detected and 14% are PLP false positives. As expected, for apex heights above 600 km the agreement is not as good. Almost a third of the

Table 1. Orbit by Orbit Statistics of the Ability of PLP to Detect Scintillation Observed by the SCINDA Network at Christmas Island

	Low Apex Alt (<600 km)		High Apex Alt (>600 km)	
	Number of Samples	Percent of Total	Number of Samples	Percent of Total
Agree				
Quiet	161	51.4%	619	51%
Active	58	18.5%	102	9%
Disagree				
PLP misses structure	51	16.3%	393	31%
PLP false positive	43	13.7%	98	9%
Total	313		1212	

cases are times when PLP does not detect structure even though the SCINDA receivers do detect scintillation. As mentioned above, the radar confirms that the scintillation-causing structure is often below the height of the field lines through which C/NOFS is passing. Hence, the satellite is simply not in the right place to measure the relevant irregularities. 60% of the cases above 600 km show apparent agreement between the ground and space measurements in that neither detect structure. It is somewhat misleading to claim these as agreements, however, because were irregularities present and causing scintillation, PLP would probably not detect them. The percentage of PLP false positives is smaller at high altitude, around half that seen at lower apex altitudes. Figure 3 is a bar graph of the data in Table 1; it highlights the apex altitude dependence in the PLP and SCINDA agreement.

[15] Given that more than half of the passes occur when SCINDA sees no scintillation it is possible that quiet times are over weighted by inclusion of passes during nonspread F season. During the test period, only the months of December, January and February averaged less than 1 h per evening of S4 > 0.2. If we exclude those months we find that passes with apex altitudes lower than 600 km have an agreement of 72%. Only the months of May and July through October averaged more than 2 h per evening of S4 > 0.2. If we limit our study to these 5 months we find that passes with apex altitudes lower than 600 km have an agreement of 68%. It does not appear that inclusion of spread F off seasons has biased the results of the study toward agreement.

5. Summary and Discussion

[16] This study looks at the ability of an in situ ion density measurement to determine if VHF scintillations caused by equatorial spread F irregularities are occurring on a link passing through the same magnetic meridian. Due to the compressed nature of the ionosphere during this period of extreme solar minimum it is unlikely that any of the in situ observations used in this study were actually made within the volume where the scintillation was occurring. Instead, those irregularities must first propagate upward into the topside ionosphere before they can be directly measured by PLP. Depending on the instability growth rate this process can occur very quickly, but observations made by the ALTAIR ISR have shown that bubble growth rates are excruciatingly slow during this level of solar activity (K. Groves, personal communication, 2008). This slow growth rate can cause substantial delays between scintillation onset and the time when the bubble is observable by PLP, if the bubble even reaches the topside. If sufficient time has elapsed between scintillation onset and the bubble reaching the topside, the F peak density may have dropped to levels where scintillation is no longer observed despite the continued presence of kilometer and smaller-scale irregularities. The observations routinely show evenings where an elevated S4 did not lead to the development of radar plumes and those where scintillation ended well before plumes rose above 400 km.

[17] For in situ observations off the magnetic equator, polarization electric fields associated with equatorial spread F irregularities must map down along field lines before they can produce structures observable by PLP. This process has been widely observed by in situ and remote sensing methods and should proceed rapidly in and above the F region [*LaBelle*, 1985; *Weber et al.*, 1996; *Basu et al.*, 1983]. Indeed, the probability of PLP observing enhanced $\Delta n_i/n_i$ when passing through a field line that maps to a region with a radar return is approximately 80% while the probability of SCINDA observing an enhanced S4 when there is a radar return above 400 km is only 60% during the same period. This indicates that the polarization electric fields are mapping along field lines effectively enough to structure the plasma in a way that is readily detectable by PLP, but that observation of those structures need not indicate the simultaneous presence of scintillation.

[18] In conclusion, as a broad predictive tool, in situ measurements of structure in the ionosphere are promising in nowcasting scintillation. However, the geometry is critical. Algorithms must account for the position of the satellite and the apex height of the field lines in judging whether the satellite observations are relevant or reliable for any given ground location.

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References

Basu, S., S. Basu, J. P. McClure, W. B. Hanson, and H. E. Whitney (1983), High resolution topside in situ data of electron densities and VHF/GHz scintillations in the equatorial region, *J. Geophys. Res.*, *88*(A1), 403–415, doi:10.1029/JA088iA01p00403.

de La Beaujardière, O., et al. (2004), C/NOFS: A mission to forecast scintillations, *J. Atmos. Terr. Phys.*, *66*, 1573–1591, doi:10.1016/j.jastp.2004.07.030.

Groves, K. M., et al. (1997), Equatorial scintillation and systems support, *Radio Sci.*, *32*(5), 2047–2064, doi:10.1029/97RS00836.

Hanson, W. B., and R. A. Heelis (1975), Techniques for measuring bulk gas-motions from satellites, *Space Sci. Instrum.*, *1*(4), 4314–4346.

Heelis, R. A., W. R. Coley, A. G. Burrell, M. R. Hairston, G. D. Earle, M. D. Perdue, R. A. Power, L. L. Harmon, B. J. Holt, and C. R. Lippincott (2009), Behavior of the O+/H+ transition height during the extreme solar minimum of 2008, *Geophys. Res. Lett.*, *36*, L00C03, doi:10.1029/2009GL038652.

LaBelle, J. (1985), Mapping of electric field structures from the equatorial *F* region to the underlying *E* region, *J. Geophys. Res.*, *90*(A5), 4341–4346, doi:10.1029/JA090iA05p04341.

Weber, E. J., et al. (1996), Equatorial plasma depletion precursor signatures and onset observed at 11° south of the magnetic equator, *J. Geophys. Res.*, *101*(A12), 26,829–26,838, doi:10.1029/96JA00440.

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